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Assembly and Installation of the Daya Bay Antineutrino Detectors

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Abstract

The Daya Bay Reactor Neutrino Experiment will make a precision measurement of $\sin^2 2\theta_{13}$, the last unmeasured angle in the neutrino mass matrix in the next few years. Assembly is well underway with 4 of the planned 8 antineutrino detectors nearing completion. Assembly and installation of these antineutrino detectors is described.

Keywords: Neutrino detector; neutrino oscillation; Daya Bay

1. Daya Bay Reactor Neutrino Experiment

The Daya Bay Reactor Neutrino Experiment [1] will measure $\sin^2 2\theta_{13}$, the last unmeasured angle in the neutrino mass matrix [2] to the best precision of the current generation of experiments. The experiment will measure the antineutrino flux from the 6 high power commercial nuclear reactors at the Daya Bay Power Plant at varying distances from the reactor cores as shown in Fig. 1. Each of two "near" detector halls contains two Antineutrino Detectors (ADs) in a common water pool. The "far" experimental hall will contain four ADs in a water pool. The water pools serve as both cosmic ray vetoes and as shielding to reduce the ambient radioactivity. Photomultipliers (PMTs) arranged in inner and outer water pool zones detect the Cerenkov light emitted by the cosmic rays. Four layers of Resistive Plate Chambers (RPCs), which are rolled over the water pools, provide additional cosmic ray detection.

A non-zero θ_{13} leads to a small deviation from the expected $1/r^2$ behavior in the number of antineutrino interactions observed as a function of distance from each core. Measuring the "far/near" flux ratio at two distances eliminates many of the reactor systematic errors which have limited the precision of previous single detector reactor neutrino experiments.

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Eight nearly identical Antineutrino Detectors (AD) detect antineutrinos through inverse beta decay interactions (IBD) on the hydrogen rich liquid scintillator target. The IBD events produce two time correlated energy signals, a positron which promptly annihilates into photons with an average energy of ~2 MeV and a neutron which thermalizes after ~10 microsecond and interacts with gadolinium in the doped liquid scintillator target zone producing a delayed ~8 MeV pulse.

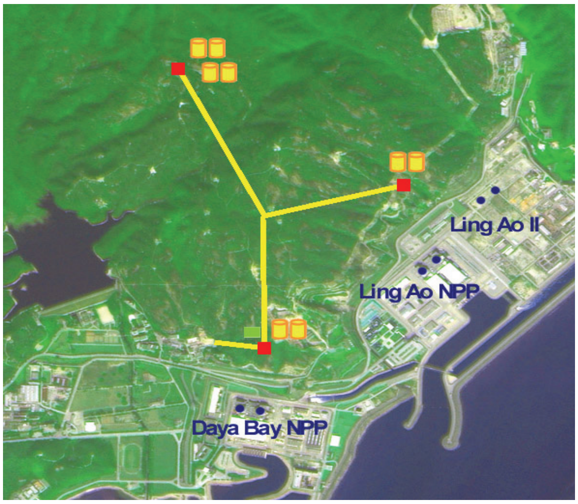

Fig. 1. The Daya Bay Reactor Neutrino Experiment has two near site Antineutrino Detector (AD) pairs and 4 ADs at the far site.

The ADs are built pairwise, to be as identical as possible, and are filled within 10 days of each other to minimize systematic differences in the antineutrino detection efficiency. One AD from each pair is deployed at the "near" site and the other at the "far" site. To further minimize systematic errors the Daya Bay design uniquely allows these AD pairs to be swapped after some period of data taking. An automatic guided vehicle (AGV) shown in Fig. 2 can transport filled ADs through the Daya Bay tunnels as needed.

Fig. 2. AD2 under transport from the Surface Assembly Building to the filling hall by the AGV.

2. Antineutrino Detector

Each AD consists of a Stainless Steel Vessel (SSV) containing 3 detector zones filled with different liquids as Shown in Fig. 3. Two nested acrylic cylinders separate the 3 zones. The target zone contains ~ 20 tons of gadolinium doped liquid scintillator (GdLS) inside an Inner Acrylic Vessel (IAV). This zone is surrounded by 20 tons of liquid scintillator (LS) gamma catcher contained by an Outer Acrylic Vessel (OAV). The final zone contains ~40 tons of mineral oil (MO) which shield the inner zones from the radioactivity of the glass PMTs and other background sources. The energy from the IBD interactions is observed by 192 PMTs arranged in a cylindrical shell (Fig. 3 and Fig. 4a). Reflectors (Fig. 4b) above and below the LS volume improve the detection efficiency.

Three automated calibration units (ACU) above the SSV lid allow the deployment of radioactive sources or LED flashers into the target GdLS volume or the LS volume. A program of calibration data runs will be interspersed with normal data taking to accurately measure and track the energy response of each AD.

Table 1. Size of the major detector components.

Component	Diameter (m)	Height (m)
Stainless Steel Vessel - SSV	5.0	5.0
Inner Acrylic Vessel - IAV	3.1	3.1
Outer Acrylic Vessel - OAV	4.0	4.0

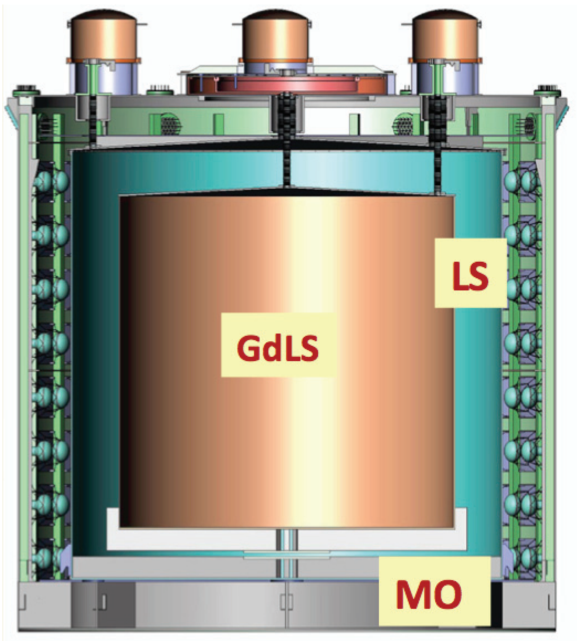

Fig. 3. The Antineutrino Detector contains 3 zones: a gadolinium loaded liquid scintillator inner target (22 tons) , a liquid scintillator gamma catcher(22 ton), and a mineral oil buffer(40 ton).

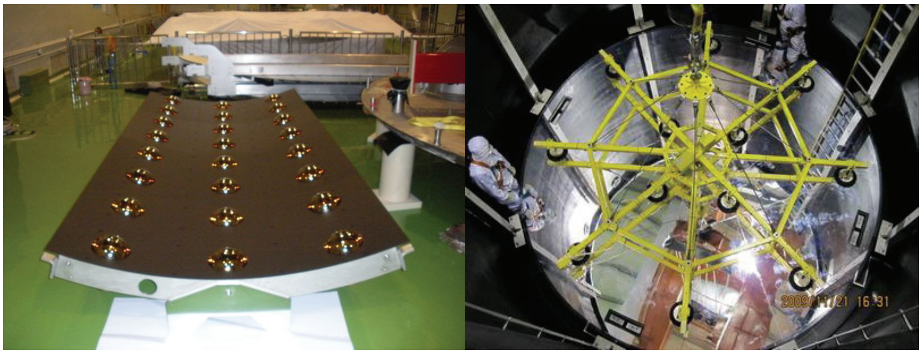

Fig. 4. (a) PMT ladder; (b) Bottom reflector being installed into a SSV.

2.1. Shipment Monitoring

The AD components of the ADs are built at multiple sites around the world. The SSVs were constructed in China, the IAVs were constructed in Taiwan, and the OAVs were built in Colorado, USA. Potential damage during shipment was a significant concern particularly for the thin walled acrylic vessels. For example, during the long shipment of the OAV from the US to China the OAVs were first loaded onto trucks and driven 1300 kilometers from an altitude of 1400 meters to sea level before being loaded onto cargo ships for a three week sea voyage. The OAVs were instrumented with multiple shock, acceleration, temperature, humidity, light, and positions sensors to record the conditions of the shipment. Acceleration and temperature histories are shown in Fig. 5. Normal freight handling did not generate any worrisome shocks. The large day/night temperature fluctuations observed at the top of the AD when exposed to the sun prompted the use of additional thermal insulation in subsequent shipments.

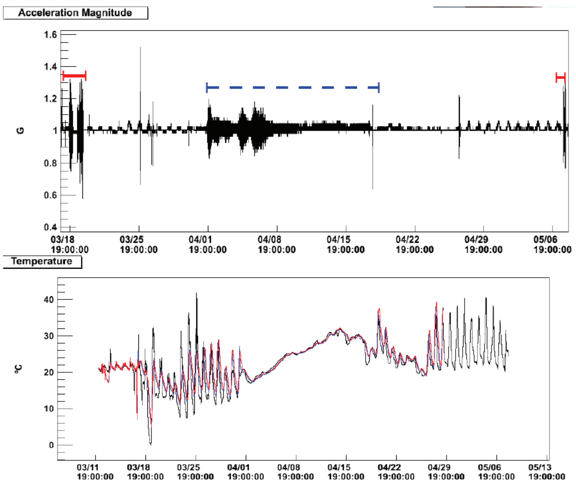

Fig. 5. Acceleration and temperature time histories are shown during the truck (red line) and ship born (blue dashed line) transportation segments. The time axis of the two plots differ. The daily temperature variations were much larger on the truck or when stored outside in the shipyard.

2.2. Leak Tests

Each AD has over 1600 o-rings and gaskets separating the 3 liquids, cover gas volumes, and water pool. Significant leaks could short an entire ladder of PMTs or could introduce systematic errors in the calculation of the target mass or change the energy calibration. After an AD is fully assembled it will be difficult to locate the source of a leak and repair would require a major intervention and disassembly of the detector. Leak checks are performed after every relevant assembly step. A goal is chosen for each joint tested. These are typically in the range of 2-5 liters of liquid in an assumed five-year operational life. The leak test is then performed using gas at a higher-pressure differential than expected for the liquid interface. Since gas viscosities are 50-200 times lower than the liquids used in an AD, desired sensitivities can be reached in a reasonable amount of time. Allowable gas leak rates between the acrylic vessels or calibration tubes are generally larger than allowable leak rates between the water pool and the lid cover gas volumes.

A variety of techniques are used: vacuum rate of rise, pressure decay, pressurizing with argon or Freon and using leak detectors to inspect the joints. Allowable gas leak rates vary with test conditions and range from 1.5 10^{-3} cc/sec for the water to SSV lid o-ring interface to 1.7 cc/sec for the MO to o-ring interface in the OAV lid. Most leakage tests test only joints. The body of the SSVs was leak checked at the factory using pressurized water. The body of the acrylic vessels is assumed leak-tight since any significant defect would be clearly visible.

As shown in Fig. 6 the major structural seals have double o-rings to enable leak tests of adequate sensitivity. The space between the o-rings is connected to a test port. In the SSV lid the space between the o-rings is pumped down to ~ 10^{-3} torr and the rate of vacuum decay is measured. Measurements are often dominated by out-gassing of the o-rings or steel surfaces. It may be necessary to pump overnight to reduce outgassing to reach the desired sensitivity. These tests have revealed problems in the early ADs. The o-ring grooves and lid surfaces in SSV1 and SSV2 had to be refinished to meet the design leak rate goals.

O-rings are used to seal the outside of the PMT cables as they pass from the MO volume inside the SSV to the gas-filled dry box in which the cables from the PMTs are connected to the longer cables to the electronics room. The MO side of a dry box seal flange is shown in Fig. 7a. Two o-rings seal the cable to the seal plug and two o-rings seal the plug to flange. The dry box flange and plugs were leak tested by applying a vacuum to the outside of flange. Experience has shown that leaks along the cable are much more common than leaks at the o-rings (although some o-ring leaks have been found).

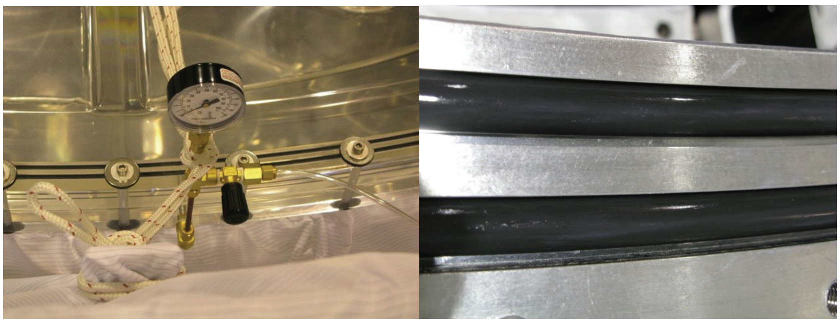

Fig. 6. (a) Outer acrylic vessel lid double o-rings under pressure decay leak test; (b) SSV lid double o-rings

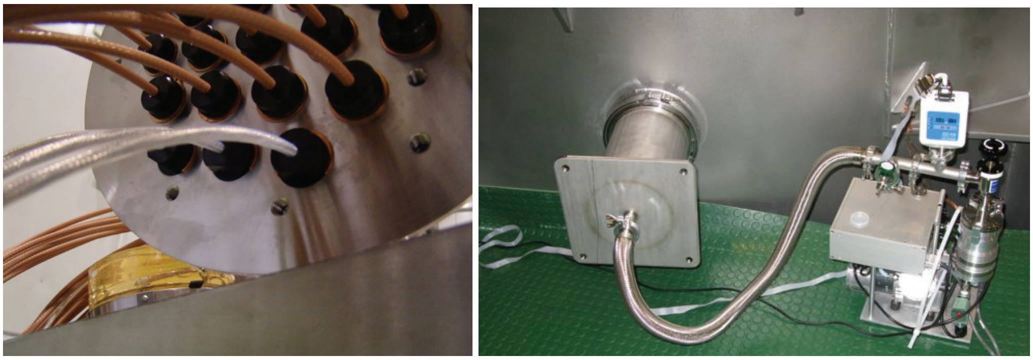

Fig. 7. (a) Cable seals on the MO side dry-box flange; (b) Vacuum test of the MO dry-box flange.

Cable leaks were caused by breaks in the outer jacket of the PMT coaxial cable, which allowed liquid (or gas) to enter the ground braid and flow to connector in the dry box. The PMT end of the cable had a gas-tight cast resin seal. The size of the leak varied with the size and distance of the jacket break from the connector, the pressure above atmosphere, and liquid viscosity. For cables inside the AD MO volume the vacuum technique described had adequate sensitivity to identify problem cables that could then be replaced. However, in the original cable design the cables to the electronics room exited the dry box through another seal plug flange and ran underwater to the edge of the water pool. The lower viscosity of the water and the water depth 2.5 m meant that allowable leak rates on the water side cables were much lower than for the MO side. Concerns about the adequacy of our leak checking capabilities lead to a significant redesign of the cable plant. The underwater cable run and water side seal plug flanges were eliminated by putting the cables inside vacuum grade SS bellows from the dry box to the surface. The present design, shown in Fig. 8a, has eliminated much of the leakage risk and has proven to be quicker and easier to install and leak check.

The acrylic vessels should not be pressurized above 15 mbar. To check the joints in the IAV or OAV calibration tubes the vessels are filled with > 75% argon as shown in Fig. 8b and pressurized to 12 mbar. An argon leak detector is then used to sniff the o-ring joints for possible leaks.

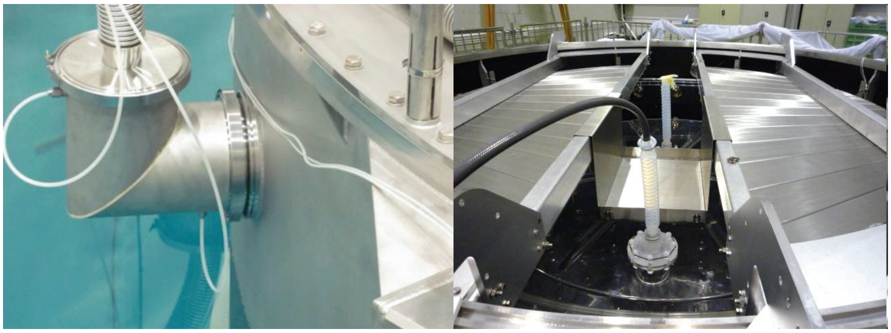

Fig. 8. (a) Water side view of the new dry box bellows design; (b) IAV calibration tubes under leakage test.

2.3. Assembly and Installation

ADs are assembled in the following sequence. The SSVs are received and cleaned before being moved into the large clean room. After surveys confirm the SSV dimensions, the PMT ladders and guide rails are test fit. The PMT ladders are then removed to have the PMTs mounted. Next the bottom reflector is installed. The OAV is installed, the OAV lid is removed, and the IAV is installed. The IAV port covers are installed (Fig. 9a) and leak tested (Fig. 8 b). The OAV lid is then reinstalled and leak tested (Fig. 6a). Populated PMT ladders (Fig. 4 a) are installed in the SSV. The upper reflector is installed and the lower part of the OAV calibration tubes are mounted. The SSV lid is installed and leak tested. Upper parts of the calibrations tubes are mated to the SSV lid and the central overflow tanks are installed (Fig. 6b). The overflow tank covers are installed. ACUs are temporarily mounted for a weeklong test of the PMTs, calibration and monitoring electronics.

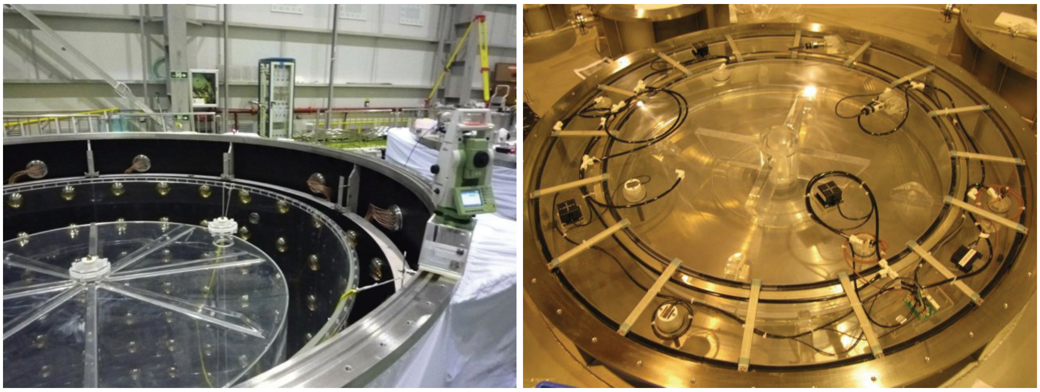

Fig. 9. (a) IAV, IAV port covers, OAV, and PMT ladders installed inside the SSV; (b) Central overflow tanks with instrumentation.

ADs are transported to the underground filling hall and then simultaneously filled with MO, LS, and GdLS. Filled ADs are moved to the experimental hall and lowered into the water pool (Fig. 10a). ACUs are reinstalled. The electrical cabling and gas lines are run through vacuum grade SS bellows from the AD to cable trays above the water level and routed to the electronics room. After final leak and electrical checks the water pool is filled (Fig. 10 b) and the RPCs are rolled in place.

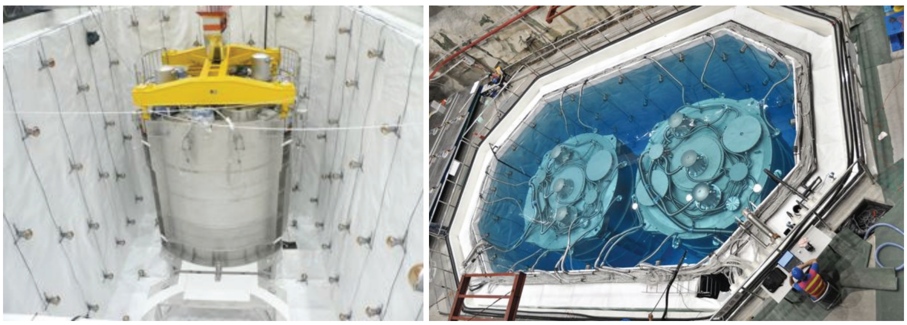

Fig. 10. (a) AD1 entering the water pool; (b) Filled water pool with 2 ADs.

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